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A Comparison of Salinity Effects from Hurricanes Dolly (2008) and Alex (2010) in a Texas Lagoon System

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ABSTRACT

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Hurricanes are not uncommon along the Gulf of Mexico coast, but there are few studies of the effects they have on coastal embayments. Hurricanes Dolly (2008) and Alex (2010) were both Category 2 storms affecting the Lower Laguna Madre (LLM) of Texas. Surveys were performed to assess poststorm water quality after landfall of both storms at up to 18 sample stations. The main difference between storm effects was salinity reduction because of stormwater input from the watershed. Effects from Hurricane Dolly were of short duration and small magnitude, whereas the effects from Hurricane Alex were extensive and lasted more than a month. Differences in spatial patterns in salinity were significantly more pronounced across the LLM than were temporal differences. Precipitation of 50–100 cm caused stormwater discharge to exceed 1000 m s^{-1} to the LLM during the Alex event and depressed salinity over more than three-fourths (ca. 500 km^2) of the estuary for 2 months. Storm-related effects on water-column physiochemistry were persistently lowest near freshwater drains (Arroyo Colorado). Salinity remained less than 5 for more than 2 months during the Alex freshet. Freshwater input from Hurricane Dolly was relatively minor because the storm precipitation was largely restricted to the small Arroyo Colorado watershed. Effects from Alex were delayed but were greater because of the bulk of the precipitation falling in the Rio Grande/Rio Bravo drainage basin in México. The greatest impact from that freshwater disturbance was the loss of seagrasses after prolonged exposure to hyposalinity. Hurricanes Dolly and Alex both affected the LLM but with contrasting impacts that reflected spatial and meteorological differences between the two storms.

ADDITIONAL INDEX WORDS *Hyposalinity, salinity recovery, freshet, Laguna Madre*.

INTRODUCTION

Effects of tropical cyclones on estuaries vary greatly. No two storms have the same environmental effects (Mallin and Corbett, 2006). Salinity decreases from precipitation and runoff are common and are often accompanied by stratification of the water column (Valiela *et al*., 1998). Stratification can lead to depression of dissolved oxygen concentrations (Stevens, Blewett, and Casey, 2006; Tomasko, Anastasiou, and Kovach, 2006). Hypoxia and anoxia can subsequently alter nutrient and metabolic processes within the system (Dix, Philips, and Gleeson, 2008; Wetz and Yoskowitz, 2013). Smaller estuaries with short water-residence times often return to prestorm conditions within days of a hurricane landfall (Valiela *et al*., 1998). Decreased water residence time and transparency also follow passage of hurricanes (Mallin and Corbett, 2006; Valiela *et al*., 1998). The watershed(s) of affected areas can deliver stormwater discharge to the estuary after the passage of a storm (Mallin *et al*., 1993). Thus, stress factors, such as hyposalinity, imposed by tropical cyclones may linger or worsen, even after skies clear.

Salinity decrease after the passage of a tropical cyclone is a stress that influences the composition, distribution, growth, and abundance of estuarine organisms. Oligohaline and freshwater fish abundance increase with decreased salinities, whereas estuarine and marine fish diversity and abundance tend to decline (Paperno *et al*., 2006; Switzer *et al*., 2006). Persistent exposure to low salinity decreased infaunal bivalve size (McLeod and Wing, 2008) and caused low growth and biomass in penaeid shrimp species areas in Barataria Bay, Louisiana (Rozas and Minello, 2011). Phytoplankton community production can be stimulated (Peierls, Christian, and Paerl, 2003), depending on the phytoplankton tolerance to a fresh or brackish water column (Boesch, Diaz, and Virnstein, 1976; Greenwood, Stevens, and Matheson, 2006; Ridler, Dent, and Arrinton, 2006; Wetz and Paerl, 2008), and community composition can rapidly shift when salinity drops (Underwood and Komkamp, 1999; Williams, Boyer, and Jochem, 2008).

Low salinity (<12) negatively affected photosynthetic performance in the mangrove *Avicennia marina* (Forsk.) Vierh. in Durban Bay, South Africa (Tuffers, Naidoo, and Willert, 2001). Seagrasses demonstrate a varied response to salinity reduction. The distribution, density, and biomass of *Syringodium*

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filiforme Kutz. (manatee grass), a stenohaline species, substantially declined after hurricanes Frances and Jeanne in 2004, with no sign of recovery the following year in the Loxahatchee River estuary, Florida (Ridler, Dent, and Arrinton, 2006). *Halodule wrightii* Aschers. (shoal grass) decreased in areal cover, whereas *Ruppia maritima* L. (widgeon grass) increased cover in the Indian River Lagoon after four tropical weather systems (Charley, Frances, Ivan, and Jeanne) (Steward *et al*., 2006). In contrast, *H. wrightii* showed little areal change in meadow distribution in Alabama coastal waters, whereas *Ruppia maritima* increased coverage after the passage of hurricanes Katrina and Ivan in 2005 (Byron and Heck, 2006). Salinity decreased to 3 after heavy precipitation in a Venezuelan marine park causing defoliation and death in *Thalassia testudinum* Banks ex König (turtle grass), which took more than 1 year to recover (Chollett, Bone, and Pérez, 2007).

Many factors contribute to the magnitude of the ecological impact by tropical cyclones. Mallin and Corbett (2006) cited landfall location, storm trajectory and speed, intensity and strength, size, tidal stage at landfall, precipitation, and infrastructure as factors contributing to the magnitude. That list did not include watershed size and proximity to an estuary or the impact of engineered flood-diversion structures and circulation patterns. These factors can influence the magnitude and duration of freshwater inflows, affecting the physical and biological properties of the receiving waters. For example, Das *et al*. (2012) found Mississippi River diversions had considerable negative effect on susceptible biota in more-saline areas of Barataria Bay (Louisiana). To understand how tropical storms affect an estuary's fundamental physiochemical and biological factors, surveys after storm passage are necessary.

Study Area

The Lower Laguna Madre of Texas (LLM) is a shallow (*ca*. 1 m), bar-built, historically hypersaline lagoon. It was affected by two storms in the past 10 years. Hurricane Dolly was a Category 2 hurricane, which made landfall directly over the LLM in August 2008, with modest precipitation (25–35 cm). Hurricane Alex (2010) made landfall about 180 km south of the LLM. The rain bands of Hurricane Alex had an immediate but modest effect on salinity. Much of the precipitation of Alex collected in the Mexican portion of the watershed of the Rio Grande/Rio Bravo and was subsequently channeled to the LLM 2 weeks later. The effects of each storm on the LLM offered a study of contrasts. Hurricane Alex was a Category 2 hurricane that made landfall in northern Mexico. A significant amount of its precipitation fell in the Mexican portion of the Rio Grande/Rio Bravo watershed, 900 km west of the LLM. Distance and storm water diversions in Texas delayed its arrival to the LLM.

The LLM has three freshwater point sources. Two are engineered drainages that carry flood waters, municipal discharge, and agricultural effluent. The third is the Brownsville watershed. The largest is the Arroyo Colorado (Arroyo). The Brownsville drainage empties into the ship channel, which connects to the southern portion of the LLM, whereas the North Floodway empties approximately 9 km north of the Arroyo (the combination are termed and considered in this article as the Arroyo). The Arroyo originates as a distributary branch of the Rio Grande/Rio Bravo, which diverges from the main channel 80 km upstream (NOAA, 2010). The Rio Grande/Rio Bravo discharges directly into the Gulf of México (Figure 1). The Arroyo is a source of most of the freshwater and a significant nutrient source of the LLM (Rio Grande BBEST, 2012). Thus, the Arroyo is the biggest freshwater point source, and its potential effects on the water column made it the focal point of this study. The objective of this study was to assess how large discharge events, such as hurricanes, affect the salinity of the LLM.

To address that objective, a series of cruises were undertaken to study the effects of hurricanes Dolly (2008) and Alex (2010) on the water column of the LLM. Changes in salinity patterns, salinity change rates, and dissolved oxygen concentrations were examined for both storms. The objective was to collect basic water-quality data for each storm because little data existed for the effect of hurricanes on the Laguna Madre, a highly productive estuary. To our knowledge, no other hurricane-impact studies for south Texas exist. Without descriptive studies such as these, insight into future storm effects and their ecological impacts are lacking.

METHODS

Sampling details and rationale are described below regarding how survey cruises were designed and conducted after each storm. Site selection and sampling frequency are presented as well as the physiochemical water-column parameters recorded. A description of the statistical design is also presented below.

Sampling Design

All cruises (after both hurricanes) were conducted along the N–S axis of the basin, generally following the Gulf Intracoastal Waterway (GIWW) (Figure 1). Sampling cruises began within 7 (Dolly) and 3 (Alex) days after landfall. For the Dolly analysis, sampling began on 1 August 2008, with subsequent cruises on 6 August, 12 August, 23 August, 26 September, 2 October, 9 October, and 7 December 2008. Initially, 27 stations were monitored for the Dolly data, but those were pared to 18 on subsequent cruises for the Alex analysis; nine of which were sampled more frequently than others. Sampling began in the Brazos-Santiago Pass, at the southernmost part of the basin (Figure 1) and proceeded northward at stations separated by approximately 4 to 8 km (see Table 1 for details and exceptions). For the Hurricane Alex part of the study, 11 sites were sampled, with 9 being the same as those of the Dolly work (Table 1). For Hurricane Alex, sampling began on 1 July 2010, with subsequent cruises made on 2 July, 11 July, 16 July, 22 July, 6 August, 21 August, 4 September, and 25 September 2010. The GIWW was used for most sampling because its depth allowed unfettered access across the long axis of the LLM. It also provided sufficient depth for stratification to occur.

Physiochemical Measurements

At each Dolly sample site, a single surface measurement for water temperature, salinity (specific conductance), dissolved oxygen (DO), and percentage of DO (%DO) was collected with a calibrated Hydrolab Quanta multiprobe within the top meter of the water column. Sites closest to the Arroyo were also sampled

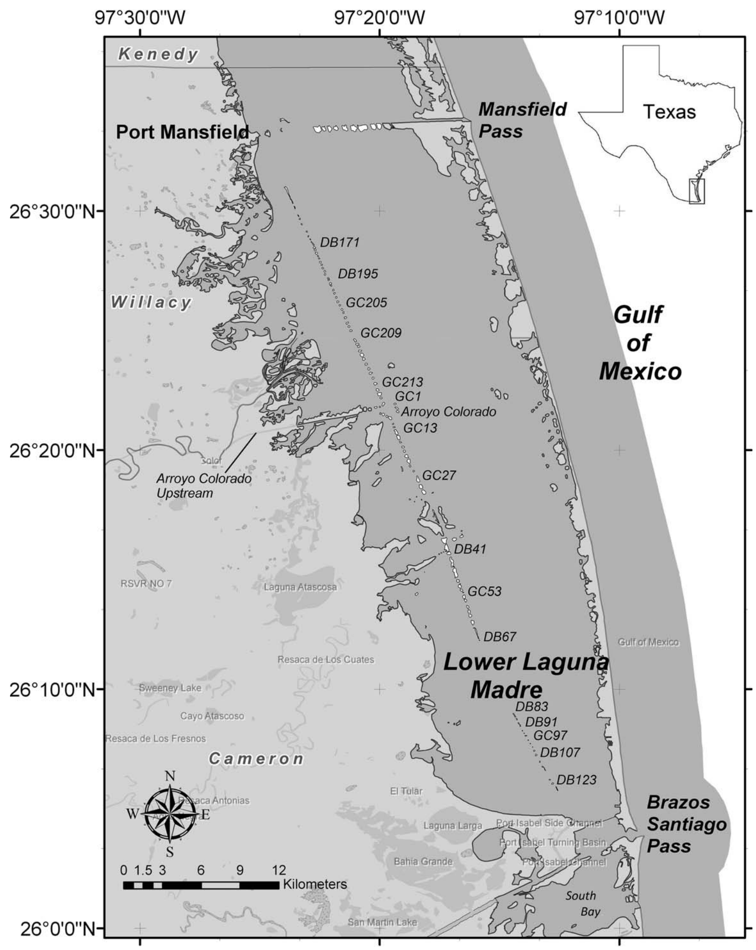

Figure 1. Map of sampling stations for Hurricane Dolly (2008) and Hurricane Alex (2010) surveys.

at depths between 2 and 3 m. For all Alex sites, salinity measurements were made at the surface and at 2 m water-column depth (data are presented only for the surface sampling to compare with the Dolly data). Rates of salinity change were calculated from the differences in salinity measurements between successive sampling dates, divided by the number of days between measurements. Positive values indicate increases in salinity, and negative values indicate decreases over time. Daily discharge flow velocity data ($m^3 s^{-1}$) (unpublished) for the Arroyo were recorded by the U.S. International Boundary and Water Commission for the gauged stations, at (El Fuste) Mercedes, Texas (26°7′47.9994″ N, 97°54′35.9994″ W) and Harlingen, Texas (26°10′12″ N, 97°42′0″ W) (provided by A. Cortez, International Boundary and Water Commission, personal communication).

Statistical Analyses

Because the same sites were repeatedly sampled through time, "sample date" was assigned the treatment level with "site" as the blocked subject (Zar, 1999) in a repeated-measures, one-way analysis of variance (RM ANOVA). Data not conforming to assumptions of normality and equal variance were square-root transformed and rerun. The Holm-Sidak *post hoc* method was used to test for significant differences among sample dates. For data still not conforming to normality, the Friedman's method of randomized blocks was used. The Friedman's test is a nonparametric alternative to the RM ANOVA and allows the use of sampling date (time) as a block with time as a substitution for replication (Zar, 1999). Friedman's randomized blocks test was used to examine differences in salinity, blocked against the site and sample date (Systat Software, Inc., 2008). An α level of 0.05 was used for all statistical tests.

RESULTS

Meteorological comparisons were made for hurricanes Dolly (2008) and Alex (2010). Poststorm water-column data were collected for 3 (Alex) to 5 (Dolly) months, which provided a baseline for comparing the nature and physiochemical effects of each storm.

Hurricane Features

Hurricane Dolly (2008) made landfall in the deep south of Texas as a Category 2 storm on 23 July 2008, along an

Table 1. *Locations, geographic coordinates of primary-transect sampling sites and reference localities, and distances among sites and localities along the Gulf Intracoastal Waterway for transect cruises, July through September 2010. See Figure 1 for spatial arrangements of sites and localities.*[a]

Sampling Site	Coordinates	Site-to-Site Reference	Distance between Sites (km)
Brazos-Santiago Pass	26°04′06″ N 97°09′34″ W	Brazos-Santiago Pass to DB123	8.5
DB123	26°07′21″ N 97°13′13″ W	DB123 to DB107	3.7
DB107	26°09′09″ N 97°14′15″ W	DB107 to DB83	5.5
DB83	26°11′52″ N 97°15′34″ W	DB83 to DB67	3.8
DB67	26°13′48″ N 97°16′15″ W	DB67 to GC13	12.5
GC13	26°20′24″ N 97°18′55″ W	GC13 to GC2	2.8
GC2 (Arroyo Colorado mouth)	26°21′39″ N 97°19′30″ W	GC2 to GC213	0.4
GC213 (Arroyo Colorado mouth)	26°21′51″ N 97°19′36″ W	GC213 to DB195	5.8
DB195	26°24′52″ N 97°20′57″ W	DB195 to DB182	4.7
DB182	26°27′13″ N 97°22′01″ W	DB182 to DB171	4.3
DB171	26°29′22″ N 97°22′57″ W	DB171 to Port Mansfield	8.4
Port Mansfield	26°33′24″ N 97°25′37″ W	Port Mansfield to [b]Rincon de San Jose	36.5
*Rincon de San Jose	26°48′30″ N 97°28′25″ W	— Total	97

Abbreviations: DB = Intracoastal Waterway Dayboard reference, GC = Intracoastal Waterway Green Can reference, navigation channel markers
[a]*The channel marking (number) system in the Laguna Madre has changed because of this study.*
[b]*Northernmost point of Lower Laguna Madre*

uninhabited stretch of South Padre Island between Port Isabel and Port Mansfield (26°4′ N, 97°30′ W) with sustained winds of 154 km h^{-1}, and 33.5–40.0 cm of precipitation between 20 and 25 July (NOAA, 2008a). Dolly produced a combined tide and storm surge of 60.96–121.92 cm (NOAA, 2008a), and the precipitation extended more than 200 km inland the day of landfall. Hurricane Alex made landfall as a Category 2 storm in northeastern México on 1 July 2010 with sustained winds of 165 km h^{-1} and produced a combined tide and storm surge of 100–150 cm, and precipitation was between 50 and 100 cm, with landfall in the states of Tamaulipas and Nuevo Leon, México (Pasch, 2010). Tropical storm–force winds associated with feeder bands from Alex extended more than 500 km north of the Rio Grande/Rio Bravo. Much of the precipitation from Hurricane Alex fell within the Rio Grande/Rio Bravo watershed; most of which lies in northeastern México. Deep southern Texas received 15–23 cm of precipitation. Cumulative precipitation and drainage filled the Amistad and Falcon reservoirs on the Rio Grande/Rio Bravo to levels that required release of excess water into the Rio Grande/Rio Bravo. Despite those efforts, the river overflowed, and floodwaters shunted through engineered diversion channels and subsequently into the LLM by way of the North Floodway and the Arroyo.

Physicochemical Characteristics

Routine physiochemical water-quality data were measured at several sample stations within 1 week of hurricane landfall for both storms. Several parameters were measured, but variations in salinity were the best indicators for assessing how each hurricane affected the LLM of Texas.

Dissolved Oxygen

DO concentrations for both Dolly and Alex study segments were significantly different over time ($F_{17,7} = 25.99$, $p < 0.001$). There was no discernable spatial pattern for either event. Overall, DO concentrations were higher and less variable with Hurricane Dolly (mostly at 7 mg L^{-1}). Concentrations for Dolly dropped at the Arroyo, with mean values between 3 and 4 mg L^{-1} over the first two sample dates, but increased thereafter to between 6 and 7 mg L^{-1} (data not shown). DO never rose above 7 mg L^{-1} in the Alex study (data not shown). Minimum DO values for Alex were between 2 and 4 mg L^{-1} and occurred for no more than 2 days.

Salinity

The effects of storm-water discharge on salinity from Hurricane Dolly were evident within 1 week after landfall (Figure 2) and followed a strong and significant (Table 2), decreasing gradient from the Brazos-Santiago Pass northward to the mouth of the Arroyo Colorado ($F_{17,7} = 16.11$, $p < 0.001$) (Figure 2). Salinity was greater than 30 nearest Brazos-Santiago Pass and gradually decreased northward, most notably in the first two sample periods (1 and 6 Aug 2008). Salinity recovered closer to ocean levels for the remainder of August 2008 until another period of precipitation 63 days after Dolly depressed salinities through the end of the year (Figure 2). Lowest salinity consistently occurred at the mouth of the Arroyo (Figure 2). After the hurricane, a combined 40 cm of precipitation fell from September to November 2008 (US Climate Data, 2008). Most of that rain (24 cm) occurred in September 2008. That pushed salinities across much of the study area to below 20 for at least 2 months. By December 2008, the end of sampling, salinities were still below 30 (Figure 2).

For the Alex study, salinities displayed strong, consistent, and statistically significant temporal and spatial patterns ($F_{10,7} = 16.77, p < 0.001; F_{12,7} = 16.02, p < 0.001$, respectively) (Table 3). Except for some fluctuations near the mouth of the Arroyo, there was a general decrease in salinity from the Brazos-Santiago pass northward to the Arroyo, followed by an increase again northward toward Port Mansfield Pass (Figure 2). Another trend in salinity was the degree of freshwater intrusion through time into the typically marine waters of the LLM, N and S of the Arroyo (Figure 2). Except for the Brazos-Santiago Pass, surface salinities dropped to about 15 by 6 August 2010, only 8 km (Dayboard123 [DB]) north of the Brazos-Santiago Pass (Figure 2). For that same date, salinities were nearly zero from DB83 to the northernmost sample site (DB171) near Port Mansfield Pass. For the months of July and August 2010, salinities in the study area were effectively zero (Figure 2). The trends in persistently depressed salinity in the LLM were also clearly seen averaged over time at all sample stations for both hurricanes (Figure 2). Mean salinity after Dolly shows a more-gradual decrease northward, as compared with the steeper slope after Hurricane Alex.

Salinity Recovery

Fastest salinity recovery rates (0.3–0.5 d^{-1}) after Hurricane Dolly occurred in the northern reach of the study area (Figure 3), although there was no significantly clear pattern and variability was sufficient to mask any potential differences among sites ($F_{17,6} = 1.03, p = 0.41$). The remaining stations had either zero or negative values, indicating continued freshening conditions for more than two-thirds of the sample stations (Figure 3). Overall, the change in mean salinity rate across all Dolly sample stations was 0.03 d^{-1} (SE = 0.06). None of the southernmost stations below the tidal cross-channel current (DB83) had positive salinity recovery rates. Salinity recovery rates after Hurricane Alex were significantly different ($F_{11,6} = 11.76, p < 0.001$). Rates of salinity change were most variable in waters between the DB83 and the Arroyo Colorado. Salinity for Alex had not recovered by the time the surveys were terminated.

DISCUSSION

The disparate effects of Hurricanes Dolly (2008) and Alex (2010) on the Laguna Madre were compared, despite both being Category 2 storms. Although landfall for Hurricane Alex was distant from the Laguna Madre of Texas, its effects were disproportionally greater than those of Hurricane Dolly. Comparisons of water-column physiochemistry and the effects of mitigating factors, such as geomorphology (watershed location and size) and engineered flood control structures were made.

Description of Each Storm

Hurricanes Dolly (2008) and Alex (2010) affected south Texas in markedly different ways. The effects of Dolly on salinity in the LLM were immediate, of short duration (<2 wk), low intensity, and had comparatively minimal effect, despite the slow-moving nature of the storm. In contrast, Hurricane Alex's rainfall took 2 weeks to reach the Rio Grande/Rio Bravo and another week to reach the LLM through the Arroyo. The LLM was affected by those low-salinity waters for 2 months.

Flow velocities of the Arroyo under low-tide, drought conditions have been measured at 3–17 $m^3 s^{-1}$ (summer 2014; unpublished data from the International Boundary and Water Commission). For comparison, Switzer *et al*. (2006) considered flows of 150 $m^3 s^{-1}$ high in the aftermath of hurricanes Frances and Jeanne (landfall 20 d apart in 2004) in the St. Lucie estuary of Florida. They found depressed salinity and near-hypoxic conditions, which persisted for several months. Maximum flow after the Hurricane Dolly landfall was 153 $m^3 s^{-1}$, but occurred only 1 day before diminishing to prestorm velocities by the middle of July 2008. Dolly was not a fast-moving storm. Because much of the precipitation that accompanied Dolly fell to the north of the Arroyo watershed, a significant portion of Dolly rainfall did not get to the LLM. Mean flow in the Arroyo for Dolly was 14.64 $m^3 s^{-1}$ (SE = 3.77; $N = 13$) for the 2 weeks before landfall, but increased to 88.05 $m^3 s^{-1}$ (SE = 16.64; $N = 8$) over the following week.

Although Hurricane Alex made landfall on 30 June 2008, peak discharge (928 $m^3 s^{-1}$) near the LLM did not occur until 19 July 2010. Before that date, the 2-week mean Arroyo discharge velocity was 26.12 $m^3 s^{-1}$ (SE = 4.54; $N = 13$). Once storm water reached the tidal Arroyo, mean discharge velocity reached 616.49 $m^3 s^{-1}$ (SE = 39.00; $N = 37$), a nearly 24-fold increase compared with Hurricane Dolly. Flows from the Alex freshet exceeded 1000 $m^3 s^{-1}$ during the first week the water reached the LLM (18–24 July 2010). The stormwater discharge (volume) resulted in water levels 0.5 to 1.5 m above mean sea level in the northernmost part of the LLM, overtopping the broad aeolian sand sheet separating the LLM from the Upper Laguna Madre, and diluting hypersaline waters there to 18 in the absence of precipitation (K. Dunton, personal communication).

Salinity

Of the physiochemical factors monitored during both studies, the best indicator for ecological impact was salinity. For Hurricane Dolly, below-normal salinities occurred from September to December 2008, with above-average precipitation for this region (NOAA, 2008b). Greatest effects on water quality from Hurricane Dolly were in the middle reach of the basin because that is where the Arroyo delivers nutrient-laden freshwater discharge (Rio Grande BBEST, 2012). At that spot, salinity and water transparency were lowest (Figure 4). Salinity was initially depressed after landfall of Dolly but had largely returned to background values within 2 weeks (Figure 2). That is attributable to the fact that the storm dropped most of its precipitation outside of the watershed. Salinity remained lower than usual throughout the wet fall of 2008 and did not rise above 20 through December 2008 across most of the study sites (Figure 2). In contrast, for July and August 2010, and a portion of September, the volume of freshwater delivered to the LLM by Hurricane Alex depressed surface salinities across much of the basin for several weeks (Figure 2). The Arroyo Colorado floodway diversion system was near capacity for more than 2 months and delivered floodwaters to the LLM. There was a clear signature of depressed salinities (between 0 and 5) at, and adjacent to, the mouth of the Arroyo, demonstrating the

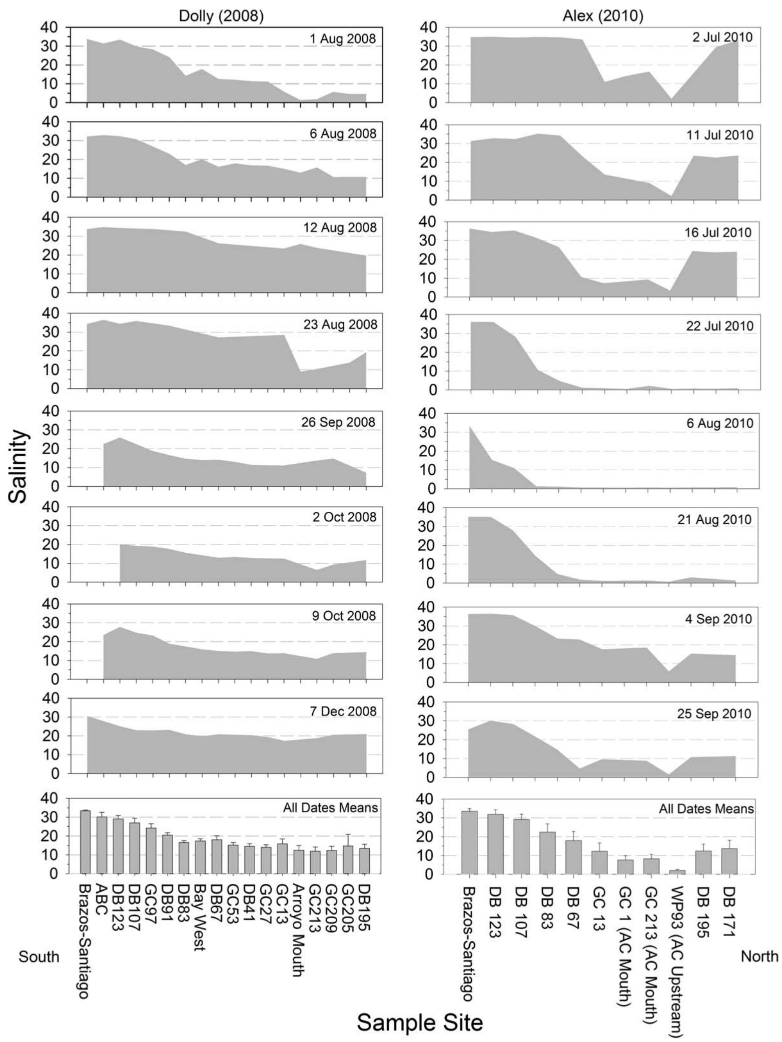

Figure 2. Area fill plots for Hurricane Dolly (2008) and Hurricane Alex (2010) surveys by respective sample sites and dates. Note the bottom panels show mean values (Error bars are SEMs). Area fills show no error factor because each value was a single sample.

effect that drain can have on the LLM (Figure 2). There was a lag period after Alex landfall before more-intense salinity effects were seen (Figure 2). Three days later, the storm salinities were between 15 and 20, thereafter falling continuously (Figure 2). Valiela *et al*. (1998) also found a lag period after passage of Hurricane Bob in 1991. There was negligible effect on the LLM from the Brownsville watershed, located in the southernmost reach of the LLM.

Throughout July 2010, and into early August 2010, freshwater continually pushed southward to depress surface salinities at DB107 and DB123 to between 10 and 15 (Figure 2). Water residence time was not calculated in this study but has been estimated to be about 90 days under typical conditions (Twilley *et al*., 1999). It is reasonable to speculate that the amount of water forced into the LLM from the Arroyo decreased water-residence times during this event. That same sort of scenario occurred in East Coast estuaries after the passage of several hurricanes (Peierls, Christian, and Paerl, 2003).

Table 2. *Results of Friedman's method for randomized blocks testing variations in surface water-column physical characteristics by sample site and against sample date along a S to N transect, Lower Laguna Madre, Texas, based on 8 cruises from August 2008 to December 2008 for Hurricane Dolly sampling.*

Dependent	χ^2	*df*	*N*	Mean Rank Dependent	Mean Rank Site	Mean Rank Date	Significance (*p* value)
Dissolved oxygen (mg L^{-1})	90.93	2	113	2.35	2.38	1.27	<0.001
Salinity	136.43	2	113	2.78	1.98	1.24	<0.001
Salinity change rates (d^{-1})	118.92	2	113	1.01	2.68	2.31	<0.001

Table 3. *Results of repeated measures one-way analysis of variance testing variations in surface water-column physical characteristics by sample site and against sample date along a S to N transect, Lower Laguna Madre, Texas, on 8 cruises from 2 July 2010 to 25 September 2010 for Hurricane Alex.*

Dependent	χ^2	*df*	*N*	Mean Rank Dependent	Mean Rank Site	Mean Rank Date	Significance (*p* value)
Dissolved oxygen (mg L^{-1})	15.19	2	92	2.10	2.22	1.68	0.001
Salinity	27.54	2	92	2.38	2.01	1.61	$<$0.001
Salinity change rates (d^{-1})	118.92	2	76	1.01	2.68	2.31	$<$0.001

For Hurricane Alex, north of the Arroyo, there was no consistent spatial pattern of salinity. This may be related to diffuse outflow from the Arroyo Colorado/North Floodway remnant historic delta/distributary system (Brown *et al*., 1980; White *et al*., 1986), as compared with the well-defined dredged channel of the Arroyo. Mallin *et al*. (1999) noted that geography can influence the degree of impact on the water column. For example, the flat topography of south Texas lends itself to more-diffuse runoff in contrast to a Piedmont uplands with the incised channels of drowned river valleys (Mallin *et al*., 1999). Given the low topographic relief of south Texas, it might be expected for drainage water to overtop natural levees and enter the LLM from several points, as is common with deltaic drainage.

Salinity Recovery

Estuarine salinity recovery is the product of mixing processes (Brock, 1998). Kelble *et al*. (2007), working in sites adjacent to the Everglades and Florida Bay ecotone over 7 years, termed salinity change rates up to –0.5 d^{-1} dramatic. Mean salinity-recovery rate in the aftermath of the Hurricane Dolly was +0.03 d^{-1}. By comparison, the surface salinity-change rate in the LLM during Alex was almost –4 d^{-1} at some sites and dates (16–20 July 2010). The mean surface salinity-change rates (–0.028) clearly illustrate the pervasive freshwater influence of Hurricane Alex (Figure 3). Not surprisingly, the intensity of that disturbance was greater, and of longer duration, at sites nearer the Arroyo (Figure 2). The greatest extent of freshwater intrusion into marine waters occurred as far south the Brazos-Santiago Pass (Division of Nearshore Research, 2010). A fairly stable halocline in the LLM developed during the Alex event at most sites and on most dates (data not shown). A 10-knot current completely mixed the water column in 1.4 days in Waquoit Bay (Massachusetts) after landfall of Hurricane Bob (Valiela *et al*., 1998). South Texas is typically windy, with velocities in excess of 5 m s^{-1} (10 knots) for more than three-quarters of the year (Brown and Kraus, 1997). This velocity would typically mix the water column, but the persistent flow of discharge for more than a month maintained the stratification, preventing mixing.

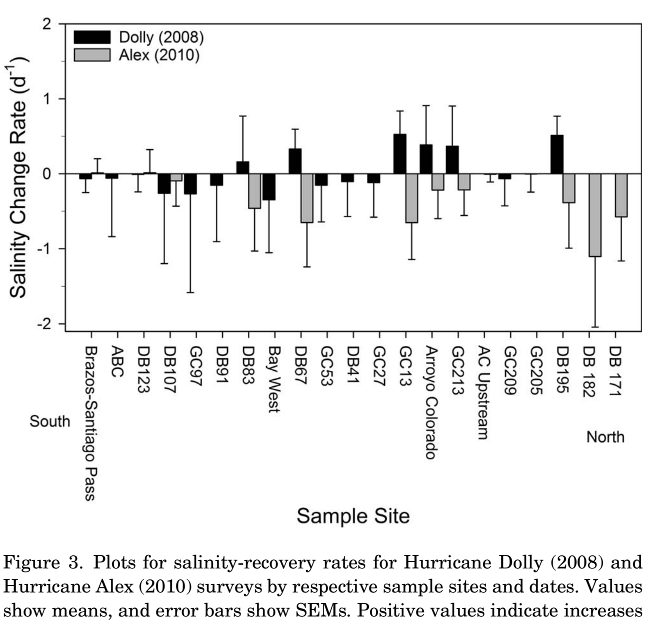

Figure 3. Plots for salinity-recovery rates for Hurricane Dolly (2008) and Hurricane Alex (2010) surveys by respective sample sites and dates. Values show means, and error bars show SEMs. Positive values indicate increases in salinity, and negative values show salinity decreases.

Several long-term LLM study sites were visually surveyed during the Dolly survey, N and S of the mouth of the Arroyo, composed of monotypic and mixed stands of *Halodule wrightii* (shoal grass), *Syringodium filiforme* (manatee grass), and *Thalassia testudinum* (turtle grass). No *T. testudinum* or *S. filiforme* was found at sites north of the Arroyo but was present at sites south of the Arroyo (personal observation). The typical pattern of prevailing SE winds advects Arroyo water northward and salinity patterns correspond with that flow (Brown and Kraus, 1997). Mean depth in this area of the LLM was about half that of the rest of the basin (0.5 m) (DeYoe and Kowalski, 2014), which may influence how pervasive the effects of freshwater discharge can be in shallow water. The fact that *H. wrightii* survived, regardless of location in this area, is attributable to the euryhaline nature of this species (McMahon, 1968). The distribution and abundance of other seagrass species N and S of the Arroyo were adversely affected. Specifically, there was basin-wide mass mortality of *T. testudinum* (58% loss) and *S. filiforme* (74% loss) that was attributed to exposure to prolonged hyposalinity (DeYoe and Kowalski, 2014) (Figure 4). Preen, Lee Long, and Coles (1995), considered a 24% loss of seagrasses along the east coast of Queensland, Australia, by two storms and a cyclone, to be an unprecedented recent occurrence. Seagrasses had not recovered in shallow water ($<$10 m) after 2 years. How seagrass populations in the LLM respond to those losses is not yet known. Beyond seagrass, there was potential for both storms in this study to significantly reset the LLM ecosystem, which warrants further study.

CONCLUSIONS

Hurricanes Dolly (2008) and Alex (2010) were Category 2 storms, but each had different trajectories with widely spaced landfall and very different effects on the water column of the LLM. A significant factor that differentiated the storms was where the rainfall occurred. The effects of any given storm arise from several factors. Landfall location, storm trajectory and speed, intensity and strength, size, tidal stage, precipitation,

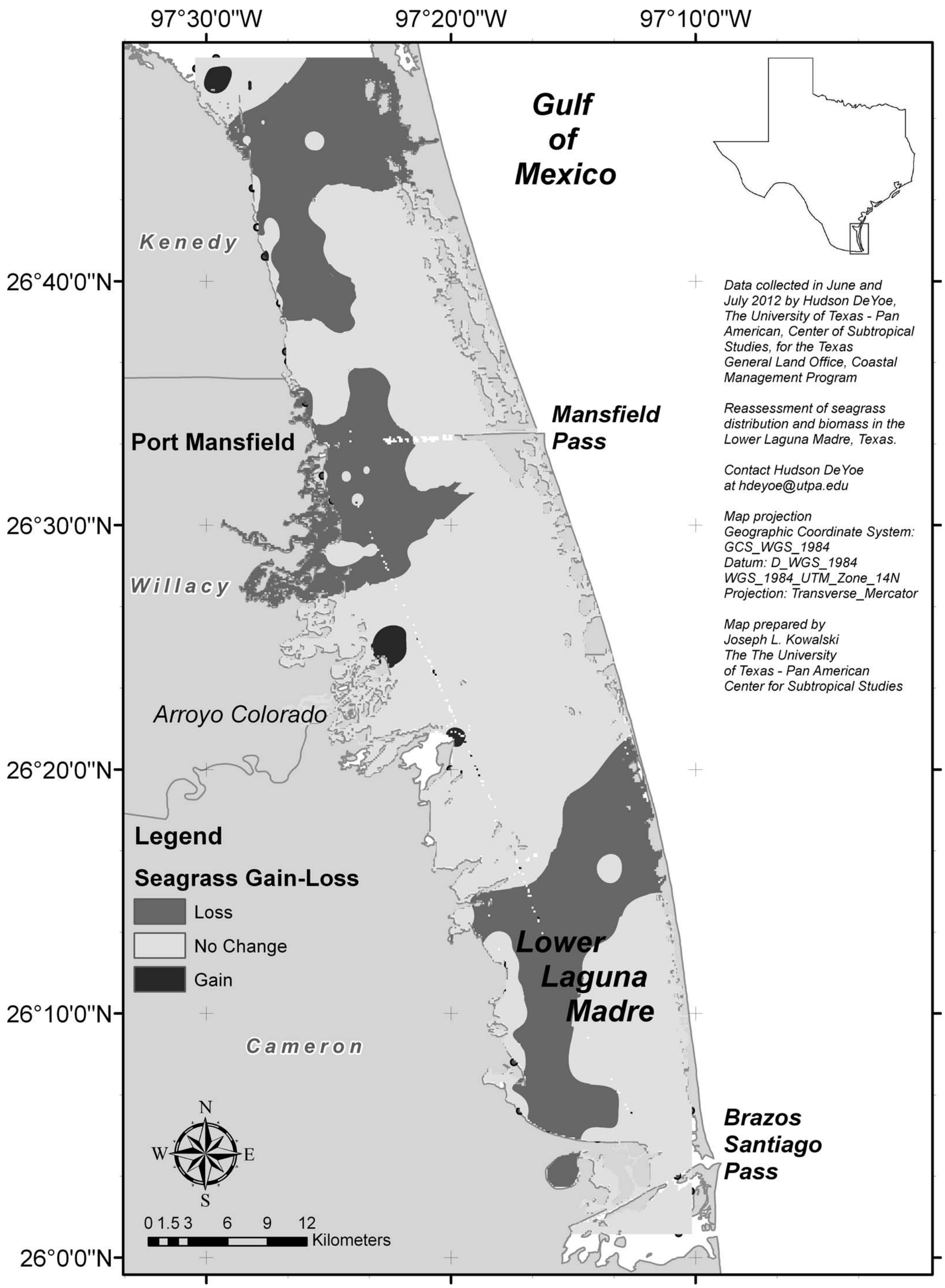

Figure 4. Change in seagrass areal cover expressed as net gain/no change/loss, relative to the presence or absence of seagrass. Map based on the difference in above-sediment biomass from Onuf (2007) and DeYoe and Kowalski (2014).

and interactions with human development (Mallin and Corbett, 2006) can influence storm impact. Storm-related precipitation in the upstream watershed must be considered, as well as the effect of engineered flood-diversion structures. The physical hydrography of the LLM water column examined in the aftermath of both storms returned to background levels within a month (Dolly) and within 6 months (Alex), respectively. The ecological toll in the immediate wake of each storm could not be determined quantitatively, but by 2014, the areal distribution of seagrass in the LLM had decreased by 58–74%

Figure 5. Photograph of seagrass leaf wrack along the sampling transect of one of the post-Hurricane Alex cruises, Lower Laguna Madre, Texas. Size of wrack mat estimated at 3–4 m. Dozens of mats of varying size were seen on the cruise.

(DeYoe and Kowalski, 1994). Substantial clusters of seagrass leaf wrack were visible for several weeks (Figure 5). Moderate freshwater discharge events can be beneficial, stimulating benthic productivity and species diversity (Alexander and Dunton, 2006; Montagna, Kalke, and Ritter, 2002), but more-intense flows of longer duration can have deleterious effects (McLeod and Wing, 2008; Montagna and Kalke, 1992; Montagna and Yoon, 1991).

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